Title: Development and assessment of management practices in a flock-specific lameness control plan; a stepped-wedge trial on 44 English sheep flocks

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Abstract

Lameness in sheep has economic and welfare implications, including loss of ewe body condition, lower lambing percentages, and poor lamb growth rates. It costs the UK sheep industry around £80 million per year. The majority of lameness is caused by the infectious diseases footrot and contagious ovine digital dermatitis, with white line separation, white line abscesses, and toe granulomas also reported by farmers. Most sheep farmers in the UK have other enterprises and care for their flock part-time. A lameness control plan (LCP) consisting of 37 management practices that covered all aspects of control of lameness was developed for part-time sheep farmers. Testing of the LCP was done using a stepped-wedge trial design with 7 visits to 44 flocks in England over 18 months. Flocks had 100-500 breeding ewes. Locomotion scoring was carried out at every visit, and farmers were interviewed every 6 months to record management practices. Clinical significance of changes in prevalence of lameness within each flock was analysed using the reliable change index (RCI). Management practices associated with prevalence of lameness were assessed using a multi-level multivariable over-dispersed Poisson model. The geometric mean (GM) prevalence of lameness at the start of the trial was

7.3% (95% confidence interval(CI)=6.3-8.3%). Flocks with a clinically significant lameness reduction had a GM prevalence of lameness of 4.6% (95% CI=4.1-5.2%), while flocks with a clinically significant increase in lameness had a GM prevalence of 10.5% (95% CI=9.4-11.6%). Always separating lame sheep at treatment (relative risk (RR)=0.60, 95% CI=0.43-0.84) and culling sheep lame ≥2 occasions in a year (RR=0.75, 95% CI=0.61-0.92) were associated with a significant reduction in lameness. Compared with not footbathing at all, footbathing sheep when there were outbreaks of interdigital dermatitis reduced lameness (RR=0.85, 95% CI=0.75-0.96), however, 'routine' footbathing was not associated with a reduction in lameness. Housing during the previous lambing period was associated with a higher prevalence of lameness (RR=1.23, 95% CI=1.04-1.46). Vaccination in flocks with period prevalence ≥10% did not significantly reduce their risk of lameness compared to lower prevalence flocks. In conclusion, separating lame sheep at treatment, culling sheep lame ≥2 occasions per year, and only using a footbath to treat outbreaks of interdigital dermatitis are flock managements that contribute to improved control of lameness in flocks with part-time farmers.

1. Introduction

Approximately 5% of sheep are lame at any time in England. Approximately 70% of that lameness is due to footrot (Winter et al., 2015), caused by *Dichelobacter nodosus,* that presents as an interdigital dermatitis or severe footrot. Left untreated for as little as one week, footrot reduces ewe body condition, lambing percentages and lamb growth rates (Wassink et al., 2010a). Footrot costs the UK sheep industry around £80 million per year (Wassink et al., 2010a). A second infectious cause of lameness is contagious ovine interdigital dermatitis (CODD), which

45 is present in 35-50% of flocks (Angell et al., 2014; Winter et al., 2015). CODD is responsible for
46 up to 33% of lameness in affected flocks, and flocks with CODD have an average geometric
47 mean (GM) lameness prevalence of 4.2%, 1.4% higher than flocks without CODD (Dickins et al.,
48 2016). Other causes of lameness include white line separation, white line abscesses, and toe
49 granulomas; farmers report that <2% of lameness is attributable to these non-infectious lesions
50 (Kaler and Green, 2008; Winter et al., 2015). Routine foot trimming is also associated with a
51 higher prevalence of lameness (Wassink et al., 2003; Kaler and Green 2009; Winter et al., 2015)
52 and is responsible for about 30% of lameness in flocks where farmers trim into sensitive tissue
53 (Grant et al., 2018).
54
55 Evidence-based management practices to control footrot and CODD include good external and
56 internal biosecurity, antimicrobial treatment of sheep within three days of onset of lameness,
57 avoiding therapeutic foot trimming, selecting replacements from non-lame ewes, and
58 vaccination against footrot (Winter et al., 2015; Dickins et al., 2016). Approximately 50% of a
59 random sample of English farmers were using some or all of these evidence-based
60 management practices in 2013 (Winter et al., 2015), an increase from 2004 (Kaler and Green,
61 2009) and probably an explanation for the reduction in the national average prevalence of
62 lameness in sheep from 10.6% in 2004 to 4.9% in 2013 (Winter et al., 2015). Although there has
63 been an increase in the number of farmers adopting the new evidence-based management
64 practices to control lameness, many farmers are still unwilling or unable to change to the new
65 recommended practices (O'Kane et al., 2017).
66

One group of farmers who might find some of the recommended management practices difficult to adopt are part-time sheep farmers. According to the Agriculture and Horticulture Development Board (AHDB), approximately 88% of flocks in the UK have less than 500 breeding ewes (AHDB, 2016). This is insufficient to provide a complete income and, consequently, many sheep farmers have secondary jobs with periods of the year away from the farm (e.g. as a contractor) and reduced time spent with their own flock. This is particularly problematic for management of the infectious causes of lameness, footrot and CODD, because delay in treatment leads to an increase in the prevalence and incidence of lameness (Green et al., 2007; Winter et al., 2015; Dickins et al., 2016).

To date (2018), there have been no clinical trials investigating treatment and control of all causes of lameness in sheep in England. In this paper we present the impact of farmer compliance with some of the management practices recommended in the lameness control plan (LCP) on the prevalence of lameness over time and identify new important management practices that influence the prevalence of lameness.

2. Materials and Methods

Ethical approval for this study was granted by the University of Warwick's Biomedical and Scientific Research Ethics Committee and the Animal Welfare and Ethical Review Committee.

2.1 Development of the lameness control plan

88 Published literature was reviewed and used, together with discussions with experts and
89 empirical observations from farmers, to identify all likely key management practices to
90 maximize control of all causes of foot lameness. These were combined to form an LCP that
91 consisted of a list of management practices. Each management practice was classed as “high”,
92 “medium” or “low” likely impact to reduce the prevalence of lameness based on the supporting
93 evidence base. Management practices were grouped into six areas; “lesion identification and
94 treatment”, “vaccination”, “biosecurity”, “footbathing”, “culling and breeding” and “housing
95 and pasture management”. A total of 37 management practices were identified (Table 1).
96
97 The recommendations made to each farmer were based on their available time and facilities, as
98 well as their compliance with management practices at the start of the study. Farmers were
99 given advice on how to treat causes of lameness present in their flock, and farmers with ≥10.0%
100 annual period prevalence of lameness were advised to vaccinate against footrot every 4-6
101 months, following the manufacturer’s instructions. Those with a monthly peak prevalence of
102 ≥10.0% at one point in the year were advised to vaccinate against footrot 2-4 weeks prior to the
103 expected peak period of lameness.
104
105 *2.2 Sample size, recruitment and retention of study participants*
106 A sample size of 44 flocks with 100 – 500 ewes per flock, visited on seven occasions, was
107 estimated based on a reduction in prevalence of lameness from 8% to 4% and a risk ratio of 1.2
108 – 3.8 (assuming an intra-flock correlation of sheep within a flock ranging from 0.1 – 1.0) with

80% power and 95% significance. The study was likely to detect risk ratios between these two extremes because sheep are neither completely dependent nor independent within a flock.

Farmers were recruited from a sub-sample of English sheep farmers who had participated in two surveys in 2013 and 2014 (Winter et al., 2015). The criteria for enrolment were that farmers were willing to participate in the study, had 100-500 ewes, a farmer-estimated annual period or monthly peak prevalence of lameness in their flock of ≥5%, and that farmers were willing to record treatments for lameness throughout the study. Three hundred farmers in England were invited to participate in the study by letter; 28/300 farmers responded to the letter and expressed an interest in participating, and a further 21 farmers were identified through follow-up telephone calls. From these 49 farmers, three were excluded at the first contact visit (two could not be reached to book the first visit and one refused to comply with our request to record lameness treatments), leaving 46 flocks.

The study was designed as a stepped-wedge cluster trial (Brown and Lilford, 2006). Flocks were stratified by geographical region; East - Norfolk, Lincolnshire, Hertfordshire, Bedfordshire, and South Yorkshire; West – West Midlands, Herefordshire, Gloucestershire, Oxfordshire, Staffordshire, Cheshire, and Shropshire; North – West Yorkshire, North Yorkshire, Cumbria, Northumberland, and Durham; South – Somerset, Devon, and Cornwall (Supplementary Figure 1) and flock size (100-250, 250-400, 400+) into pairs and then a coin was tossed to allocate one of each pair to each tier. Twenty-three (50%) farmers were provided with their LCP 2-4 weeks after their first visit (tier 1 flocks) and the remaining 23 farmers were provided with their LCP 2-

4 weeks after visit 3 (tier 2 flocks). From the 46 flocks, five left the study after visit 3 (one farmer sold his flock and four farmers cited a lack of time to commit to the study); two were from tier 1 and three from tier 2. All data from the two tier 1 participants who withdrew were excluded because their intervention data were incomplete. Baseline data from the three tier 2 participants were retained for analysis, as no intervention was attempted. At the end of the study there was baseline data from 90 visits to 44 flocks and intervention data from 206 visits to 41 flocks.

2.3 Data collection

2.3.1 Baseline data to inform the lameness control plan for each flock

Visits were conducted approximately every 3 months by one researcher (JW), with an assistant supporting some visits. The first visit to each flock was conducted as soon as possible after a farmer was enrolled. At this visit, farmers signed a consent form and provided contact information for their veterinarian, who was subsequently notified that their client was enrolled in the study. All participants were asked to provide current data on flock size, average annual period prevalence of lameness, and management of footrot. Tier 1 farmers were asked additional questions to construct their LCP, including details of lambing, weaning and breeding schedules, other work they had on and off the farm throughout the year, and treatment methods for all causes of lameness. These same questions were asked of tier 2 farmers at visit 3 to construct their LCP.

2.3.2 Data collected by the researcher at visits 2 – 7

153 At visits 2-7, the locomotion score (Kaler et al., 2009) of all sheep in the flock, or a
154 representative group of at least 15% of the flock, were recorded. Locomotion scores were
155 recorded on a commercial smartphone app (Advanced Tally Counter Pro™). Results were saved
156 in a CSV file to the researcher's telephone, then emailed with the date and time of scoring.
157
158 Farmers were interviewed at visits 3, 5 and 7 on management practices carried out in the
159 previous 6 months. These interviews included questions on a Likert-type scale of "Always",
160 "Usually", "Sometimes", "Occasionally", or "Never" (Likert, 1932) to establish the degree of
161 compliance with each management practice in their LCP.
162
163 *2.3.3 Methods for on farm data capture by farmers*
164 Throughout the study, farmers were asked to record all treatments and preventions for
165 lameness. They made these recordings using one of three options: continued use of their
166 existing recording system, a project-specific paper form, or a smartphone app that was
167 specifically designed for the project. The app was compatible with both iOS and Android
168 operating systems, and available for download through the Apple App Store or Google Play. An
169 online website portal was created for farmers who wanted to submit digital data directly via a
170 computer. Farmers were given a unique farm ID and password to access the digital systems.
171
172 *2.4 Data storage and merging*
173 Locomotion score data were downloaded from the tally counter app and merged into a central
174 Excel spreadsheet. Interview data were manually entered into an Access database, and later

exported as an Excel file and merged with the locomotion score data. Treatment records submitted on paper forms were manually entered into a separate Access database, while data submitted via the app or online portal were downloaded and saved in an Excel file then merged with the paper forms in their Access database.

2.5 Data analysis

2.5.1 Analysis of change in prevalence of lameness over time

The prevalence of lameness on each farm at each visit was the percentage of sheep observed with a locomotion score >1 (Kaler et al., 2009) at that visit. The prevalence of lameness was positively skewed, so the GM prevalence of lameness was used for estimates of the mean.

The reliable change index (RCI) was used to assess the change in within flock prevalence of lameness over time (Jacobson and Truax, 1991) using the equation below:

$$RCI = \frac{X_2 - X_1}{\sqrt{2\,(s\sqrt{1 - r_{xx}})^2}}$$

Where X_1 is the baseline prevalence of lameness (visit 1 for tier 1 flocks and visit 3 for tier 2 flocks) in a given flock and X_2 the prevalence of lameness at subsequent observations, s is the standard deviation of all recorded baseline data, and r_{xx} is the test-retest reliability measured on a scale from 0.0001-0.9999; r_{xx} was set at 0.90 because locomotion scoring is highly repeatable within observer (Kaler et al., 2009). Significance was determined using the following equation:

195 $$\pm 1.96 \times \sqrt{2\,(s\sqrt{1-r_{xx}})^2}$$

196 Significant negative RCI results indicate a clinically significant reduction in lameness prevalence,
197 while significant positive results indicate a clinically significant increase in lameness prevalence.
198
199 *2.5.2 Analysis of causes of lameness over time*
200 Using complete treatment data provided by 10 participants, the monthly period prevalence and
201 incidence rate of treatments per lesion per month were calculated.
202
203 *2.5.3 Multivariable mixed effects model of management variables and their association with*
204 *prevalence of lameness*
205 There were 48 explanatory variables tested in the model; the 37 recommended management
206 practices from the LCP and 12 further variables. These 12 variables were the lameness
207 prevalence at visit 1, the lameness prevalence at the previous visit, whether the flock was
208 housed during the previous lambing season, the number of weeks housed, whether the flock
209 had CODD, regional average temperature (°C) and cumulative rainfall (mm) for the month prior
210 to the visit, percentage compliance with all recommendations, weeks the flock had been in the
211 study, weeks the flock had been on their LCP, and whether the farmer kept accurate treatment
212 records. Whether a flock had >15% lameness prevalence at a visit was tested in the final model
213 to improve model fit.
214
215 Analysis was carried out in MLwiN version 2.35 (Rasbash et al., 2014) using a two-level over-
216 dispersed Poisson model. The model took the form:

$$Y_{ij} \sim OFFSET + \beta_{0j} + \beta x_j + \beta x_{ij} + u_j + \pi_{ij}$$

where Y_{ij} is the actual count of lame sheep with a log link function (~) to *OFFSET*, the log of the expected number of lame sheep in a flock at a visit. In addition, β_0 is the intercept, βx is a series of vectors of fixed effects that vary at *j* (flock) and *i* (visit), u_j is the residual variance between flocks, and π_{ij} is the variance between visits in the over-dispersed model. This was calculated from the mean prevalence of lameness across all farms for that visit adjusted by flock size. The model was fit using the marginal quasi-likelihood method with first order derivation of the Taylor series expansion and iterative generalised least squares estimation.

A forward manual stepwise model was built based on the univariable results. Alpha was set at 0.05 using Wald's test such that $p \leq 0.05$ when 95% confidence intervals of the relative risk did not include 1.00. To investigate underlying patterns in the data before the explanatory variables from the LCP were investigated, week of study and week on plan were tested in the model as polynomial variables up to ^4 to investigate the underlying distribution of prevalence of lameness over calendar time and time on plan. The prevalence of lameness at visit 1, the prevalence of lameness at the previous visit after visit 1, tier and baseline/intervention visit type were forced into the model.

Where two variables were a strongly correlated (Spearman's $r_s \geq 0.60$), the most biologically plausible variable was left in the model. Continuous variables other than time were investigated for linearity by categorising them into 5 groups and comparing these with the outcome variable. Interactions between variables were not examined because of the relatively small

study size. The model fit was investigated by comparing the distribution of the observed and predicted outcomes from the model ranked into quantiles of the observed data. These were compared visually (Supplementary Figure 2).

3. Results

3.1 Uptake of recommended management practices and farmer compliance throughout the study

There were 8 recommended management practices that >50 % of farmers were using at the start of the trial; these were not practising routine foot trimming (54.5%), checking the flock daily for lameness (86.4%), treating lambs with interdigital dermatitis with topical antibiotic spray (52.3%), using a footbath to treat outbreaks of interdigital dermatitis (79.5%), treating lame ewes within 1 week of onset of lameness (81.1%), resting pastures for at least 2 weeks between sheep grazing them (52.3%), having stock-proof fencing around all farm boundaries and isolation areas (84.1%), and having stock-proof fencing for all fences (70.5%) (Supplementary Table 1).

Compliance with management practices was highly variable at the start and over the course of the study. Compliance increased most for stopping routine and therapeutic foot trimming, using injectable antibiotics to treat footrot, and culling ewes lame on ≥2 occasions within a year. Compliance decreased over the study for treating sheep within either 3 days or one week of onset of lameness, footbathing during outbreaks of interdigital dermatitis, and scraping out pens with groups of ewes at least once during the housing period, especially over visits 6 and 7.

No farmers reported using separate clothing or footbaths for isolations areas, so this management practice was removed from further analyses.

3.2 Prevalence of lameness over time

The initial flock prevalence of lameness ranged from 5.0-15.0% with a GM prevalence of lameness for tier 1 and tier 2 flocks of 7.7% and 7.0% respectively (Figure 1). Over the first year of the study, the GM prevalence of lameness in tier 1 flocks fell from 7.7% (CI=6.1-9.3%) before intervention, to 4.7% (CI=3.5-5.8%) at visit 5. Tier 2 flocks' GM prevalence of lameness rose from 7.0% (CI=5.7-8.2%) to 7.4% (CI=6.2-8.5%) at visit 3, the visit before the intervention, then decreased to 5.6% (CI=4.4-6.7%) at visit 5. Some flocks in both tier1 and tier 2 had an increase in prevalence of lameness at visit 6; GM prevalence 5.3% (CI=4.3-6.4%) and 6.8% (CI=5.6-7.9%) respectively. At visit 7, the GM prevalence for tier 1 increased to 7.1% (CI=4.6-9.6%), while the GM prevalence in tier 2 flocks remained similar at 6.7% (CI=4.4-9.1%). This is summarised by region in Figures 2a-d; whilst many flocks had a reduction in prevalence of lameness over the whole study and maintained a prevalence of lameness below their initial baseline, some flocks had large increases in prevalence of lameness at visits 6 and 7, with 6 flocks having a prevalence of lameness 2- to 3-fold higher at visit 7 than at visit 1.

From the RCI, there was a significant decrease in the prevalence of lameness at each visit for up to 62% of tier 1 and up to 45% of tier 2 flocks, and typically a greater number of flocks saw a decrease in lameness prevalence than an increase or no change (Table 2, Figures 3a-b). The exception for tier 1 flocks was visit 7 where 10 flocks had an increase in prevalence of lameness.

283 Tier 2 flocks had eight flocks with increased and decreased prevalence of lameness at visits 4
284 and 6. A total of 29 (71%) flocks had a significantly negative RCI for at least one visit. The GM
285 prevalence of lameness in flocks with a significantly negative RCI was 4.6% (CI=4.1-5.2%), 5.9%
286 (CI=5.3-6.5%) in flocks with no significant change, and 10.5% (CI=9.4-11.6%) in flocks with a
287 significantly increased RCI.
288
289 *3.3 Disease incidence rates over time*
290 Treatment records were submitted from 38 (86.4%) farmers during the study, however, only 10
291 (22.7%) submitted complete records from their enrolment date to the final visit. These 10
292 flocks submitted a total of 1,566 treatments records citing 1,651 incidents of disease. There
293 were 740 (44.8%) cases of interdigital dermatitis, 694 (42.0%) severe footrot, 88 (5.3%) white
294 line separation, 70 (4.2%) toe granuloma, 42 (2.5%) CODD, and 17 (1.0%) white line abscesses.
295 The monthly incidence and proportional morbidity by lesion is presented in Table 3. Over the
296 study, there was a trend for an increase in cases of interdigital dermatitis and a decrease in
297 cases of severe footrot (Figure 4). The occurrence of the remaining conditions varied over time
298 without any obvious trend. Within these 10 flocks, 6.2% (range=2%-14.2%) of sheep were lame
299 on ≥2 occasions within a calendar year, and 1.94% (range=0-5.4%) were lame on ≥3 occasions
300 within a calendar year (Supplementary Table 2). Sheep that were lame on ≥2 occasions
301 accounted for an average 43.8% (range=22.0-66.3%) of all recorded treatments.
302
303 *3.4 Univariable analysis of management variables and their association with lameness*
304 *prevalence*

305 Univariable analysis results are presented in Supplementary Table 3. Separation of lame sheep
306 at the time of treatment was strongly correlated with having a separate field/pen for isolation
307 (r_s=0.66). It was of greater interest to this study to evaluate the impact of farmers separating
308 lame sheep rather than having the possibility of doing so, consequently separation of lame
309 sheep was selected for testing in the model.
310
311 *3.5 Multivariable multi-level model of management practices associated with prevalence of*
312 *lameness*
313 The results of the final multivariable model, including RR and 95% CIs, are outlined in Table 4.
314 Of the variables forced into the model, initial and previous prevalence of lameness were
315 strongly associated with a higher risk of lameness at a visit, while week in study, tier and
316 baseline/intervention visit variables did not significantly influence the risk of lameness,
317 indicating that there was no underlying difference between flocks by time, tier and data type.
318 The 4-level polynomial 'week on plan' was significantly associated with risk of lameness when
319 only the above variables were in the model, with all 4 terms significant (Supplementary Table 4)
320 indicating the non-linear pattern of prevalence of lameness. This significance disappeared once
321 the management variables were in the model. Culling sheep lame on ≥2 occasions within a
322 calendar year and separating all lame sheep throughout the year had lower risks for lameness.
323 Flocks advised to vaccinate against footrot because the prevalence of lameness was ≥10% had a
324 significantly higher risk of lameness from flocks with <10% prevalence of lameness where
325 vaccination had not been advised, regardless of compliance. Compared to flocks that were not
326 footbathed at all, using a footbath to treat outbreaks of interdigital dermatitis was associated

with a lower risk of lameness; however, routine footbathing had no significant association with reduced risk of lameness. Flocks that had been housed during the previous lambing season had a higher risk of lameness.

The level 1 residuals were a reasonable fit to a normal distribution. The level 2 comparison of observed versus expected was reasonable with a slight over-prediction of low prevalence of lameness and under-prediction of high prevalence of lameness (Supplementary Figure 2). The model fit was improved when a prevalence of lameness >15% variable was included in the model (model not shown) to account for visits with a very high prevalence of lameness. This term had no significant effect on the other explanatory variables in the model.

4. Discussion

The current study is the first to provide evidence in a clinical trial that culling sheep that have been lame on ≥2 occasions within a year and separating lame sheep until recovered reduce the prevalence of lameness. It also contributes to understanding of the role of footbathing and housing sheep over the lambing period. The number of weeks on the LCP, visit type, and tier were forced into the model, but none were significant in the final model, indicating that any differences in tier, time on plan and visit type were explained by the risk factors in the final model. These management activities are discussed below.

Culling ewes with two or more episodes of lameness within a year reduced the prevalence of lameness by removing ewes with chronic disease that are likely to spread disease within the

flock (Witcomb et al., 2014; Maboni et al., 2016), or ewes with non-infectious causes of lameness that did not respond to treatment, such as a toe granuloma. These repeatedly lame ewes accounted for approximately 44% of all recorded treatments, representing a significant cost in time and money. Only 6/44 farmers were compliant with this recommendation (Supplementary Table 2), highlighting that culling sheep lame ≥2 occasions is not a common practice. From the treatment records from the 10 flocks, an average of 13 (6.2%) with a range of 6-31 (2-14.2%) ewes were lame on ≥2 occasions (Supplementary Table 2). The average culling rate per year in UK is 20-25% (AHDB, 2015) and average annual ewe mortality is 4-6% (AHDB, 2015), so most farmers could practise 10-15% discretionary culling that could be focused on removing sheep lame on ≥2 occasions in a year. The results from the current study strongly support culling ewes that have been lame ≥ twice in a calendar year as part of a lameness control plan. In contrast, 20/44 (45.5%) farmers culled ewes lame on ≥3 occasions, and this did not have a significant impact on the risk of lameness, indicating that it was not an effective practice.

The current intervention study also provides strong evidence that always separating lame sheep at treatment was associated with a lower risk of lameness. Only 2/44 farmers implemented this practice, but the variable was significant in the multivariable model (Table 4) indicating a strong association. A similar result was reported in a retrospective observational study of lameness in 2000 when 12/164 (7.3%) farmers reported always separating lame sheep, which was associated with a reduction in the risk of lameness (Wassink et al., 2003). This indicates sheep remain infectious for a period after treatment, so separation stops spread of disease by

371 reducing the bacterial load on pasture and bedding and reducing contact between infectious
372 and healthy sheep. These studies combined highlight the powerful effect of separating lame
373 sheep at treatment, and that it is a practice that should be adopted whenever possible.
374 Farmers that did not separate lame sheep cited a lack of separate space and limited time to
375 manage a separate group of sheep. In fact, by not adopting this management practice, farmers
376 were spending considerable time catching and treating lame sheep that might not have become
377 lame if farmers had separated lame sheep at treatment.
378
379 This is also the first intervention study to clarify when footbathing is effective in the UK. We
380 conclude that footbathing is effective for treatment of outbreaks of interdigital dermatitis but
381 not as a routine practice. This result is the same as that reported in retrospective observational
382 studies from the UK (Wassink et al., 2004; Kaler and Green, 2009; Winter et al., 2015). The
383 evidence from the current study suggests that there is no benefit to routine footbathing
384 compared with not footbathing (Table 4). In 2006, farmers reported that they were dissatisfied
385 with the efficacy of footbathing but also viewed it as an ideal way to control footrot, indicating
386 cognitive dissonance (Wassink et al., 2010b). It appears that, 10 years later, farmers are still
387 using an ineffective management tool possibly because they view it as an “ideal method”,
388 regardless of its efficacy. In contrast, in Wassink et al (2010b), farmers reported that they
389 wanted to stop foot trimming, also an ineffective management, and they have been receptive
390 to this recommendation, with only 60% of farmers routinely foot trimming their sheep in 2013
391 (Winter et al., 2015) and 45% at the start of the current study. Although stopping footbathing

392 would save time and money (Wassink et al., 2010b; Winter and Green, 2017), some farmers
393 beliefs still need to be altered before they will stop routinely using footbaths.
394
395 There is only one licensed vaccine against footrot (Footvax™, MSD). It has a duration of effect of
396 4 – 6 months, an efficacy of approximately 60% (Duncan et al., 2012) and on average reduces
397 the period prevalence of lameness by 20% (Winter et al., 2015). The vaccine adjuvant is an
398 irritant and sometimes produces swellings at the injection site that are disfiguring and can be
399 damaged during shearing. The vaccine costs £1 per injection, so for the annual course of two
400 injections per sheep it would cost a flock of 500 sheep £1000 per year, and £1500 per year if a
401 single booster injection is given after 6 months. Because of the high cost to benefit ratio, the
402 LCP recommendation was to target vaccination on the flocks where the monthly or annual
403 period prevalence of lameness was ≥10%; double the national period prevalence of lameness.
404 There was no significant difference in lameness prevalence between flocks that were compliant
405 with this recommendation versus those that were not, and the prevalence of lameness
406 remained high in these flocks compared with flocks where vaccination was not recommended.
407 Sheep would have been vaccinated against footrot for a maximum of 12-18 months, and this
408 might be one explanation for its lack of benefit, as might power in the study to detect a small
409 change in risk of lameness. We conclude the time to benefit and cost effectiveness of a
410 vaccination programme needs to be considered in an LCP.
411
412 In the UK, housing sheep is common practice in winter to prevent poaching of pastures and to
413 feed and monitor ewes before and during lambing. Damp straw bedding is an ideal

414 environment for the survival of *D. nodosus*. Many farmers report an increase in the prevalence
415 of lameness during winter housing (Wassink et al., 2003; Winter et al., 2015), and the current
416 study confirms those reports: housing the flock in the previous lambing season was associated
417 with an increase in the prevalence of lameness compared with not housing sheep (Table 4).
418
419 The flocks in the study were selected because they had high prevalence of lameness and the
420 farmers had other employment than sheep. Some of the recommendations in the LCP were
421 already being done by the majority of farmers (Supplementary Table 1), so it was not possible
422 to investigate these managements. Compliance with management practices was based on
423 farmer self-reporting. If misclassification bias resulted from over-reporting of management
424 practices, the efficacy of management practices would be underestimated in the model; for
425 example, whilst farmers were aware of the merits of inspecting animals before purchase and
426 treatment of lameness within three days of onset, implementation varied, and some farmers
427 may have not wished to admit this to the interviewer. Farmers also provided several reasons
428 why they may have not complied with some of the recommended management practices. Lack
429 of handling facilities was frequently highlighted; most flocks were grazed on fields that were
430 several miles apart, and many farmers did not have the finances to build permanent facilities in
431 every field or to purchase a mobile handling system. In addition, some farmers avoided
432 handling ewes during the mating season or whilst heavily pregnant, citing concerns about
433 causing low pregnancy rates and abortions, respectively. Some farmers were hesitant to catch
434 and treat ewes with young lambs, concerned that the lambs would be separated from their
435 dam or that they would be trampled. The harvest period was another challenge. This varies by

436 crop (cereals: August-September, potatoes: August-October, orchard fruits: September-
437 November) and is highly weather dependent. Days that are too wet for harvesting are also not
438 suitable for handling sheep, so the flock may not be handled for several weeks until the harvest
439 is complete. Most farmers encountered one or more of these issues that prevented prompt
440 treatment of lame sheep during the study.
441
442 Despite the challenges to comply with the LCP, the overall prevalence of lameness decreased
443 until visit six (Table 2), the number of farmers complying with some recommendations
444 increased (Supplementary Table 1) and the number of causes of lameness decreased in the
445 preceding 6 months (coded as "Not Advised" (Supplementary Table 2)) including some
446 reporting no cases of severe footrot by the end of the study (Figure 4).
447
448 The importance of following the LCP is highlighted by the final 6 months of the study, when an
449 inability to catch and treat lame sheep occurred in some flocks. There was high rainfall in some
450 areas that led to flooding and some farmers reported that lame sheep could not be treated
451 promptly. The variability in the GM prevalence of lameness and the number of outlier visit
452 prevalence of lameness increased in the North, West, and South regions (Figure 2).
453
454 **5. Conclusions**
455 In this 18-month intervention study of sheep flocks with a period prevalence of lameness ≥5%,
456 mostly attributable to footrot, there was a significant reduction in prevalence of lameness in
457 most flocks following implementation of a Lameness Control Plan. Always separating lame

458 sheep at treatment and culling sheep that were lame ≥2 occasions in a year were associated
459 with a significantly lower prevalence of lameness. Footbathing during outbreaks of interdigital
460 dermatitis was also associated with lower prevalence of lameness compared with flocks that
461 never footbathed, however, routine footbathing of the flock did not reduce the prevalence of
462 lameness, indicating this is an ineffective practice. Vaccination against footrot in flocks with
463 ≥10% prevalence of lameness did not significantly reduce the prevalence of lameness. Housing
464 compared with not housing was associated with a higher prevalence of lameness. Farmers who
465 continued to implement the LCP in poor weather conditions, and whilst having other
466 responsibilities, had substantially lower prevalence of lameness in their flock compared with
467 farmers not compliant with their LCP.
468
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472
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475 Naomi Prosser for their assistance during farm visits.
476

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561 Table 1. Management practices in the lameness control plan by area grouping and likely impact

Area	Impact	Management practice
Identification and treatment of lesions	High	No routine foot trimming
		Daily inspection of flock
		Treat lame sheep within 3 days
		Treat severe footrot with long-acting antibiotics and topical spray
		Treat contagious ovine digital dermatitis with long-acting antibiotics and topical spray
		Treat ewes with interdigital dermatitis with long-acting antibiotics and topical spray
		Treat lambs with interdigital dermatitis with topical spray only
		Remove debris in white line separation and treat with long-acting antibiotics and topical spray if infected
		Treat white line abscesses with long-acting antibiotics and topical spray
		Do not trim diseased feet as a form of treatment
		Keep treating lame sheep throughout pregnancy
	Medium	Treat toe granulomas with anti-inflammatory, consider culling the sheep
		Footbath during outbreaks of interdigital dermatitis
		Treat lame sheep within 1 week
Vaccination	Medium	Vaccinate against footrot every 4-6 months or 2-4 weeks before risk period
Biosecurity	High	Isolate new and returning sheep for 28+ days
		Inspect all feet of new and returning sheep, treat as needed
		Separate lame sheep at all times, return to the flock when they have no signs of clinical disease
	Medium	Separate lame sheep at key times of year, return to the flock when they have no signs of clinical disease
	Low	No co-grazing with cattle
		Have separate boots or a bootwash for isolation areas
		Spread lime in high moisture areas
Footbathing	Medium	Footbath all sheep when in for other treatment; do not gather for routine footbathing
Culling and Breeding	High	Cull sheep with 2 or more cases of lameness within a year
		Avoid selecting replacements from offspring of ewes being culled for lameness reasons
		Inspect all sheep before purchasing them
		Purchase all sheep from a single private source
	Medium	Cull sheep with 3 or more cases of lameness within a year
		Ask sellers for flock disease and lameness history
Housing and Pasture Management	High	Rest pastures for 2+ weeks between grazing groups
		Have a separate field/pen for sheep isolation
		Top up bedding frequently during housing to keep the environment dry under-foot
		Disinfect individual pens after each use during housing
		Stock-proof fencing for all property boundaries and isolation areas
	Medium	Scrape out group pens and re-bed them at least once during housing
		Double-fence all property boundaries shared with neighbours with livestock
		Stock-proof fencing for all fences

562

563 Table 2. Number (percent) of 44 flocks in England from 2014-2016 by tier contributing baseline
564 and intervention data, and where the reliable change index (RCI) indicated a decreased,
565 unchanged, or increased prevalence of lameness compared with the baseline before starting
566 the lameness control plan (tier 1=visit 1, tier 2=visit 3)

Tier	**Visit No.**	**No. Flocks**	**Decreased No. (%)**	**Unchanged No. (%)**	**Increased No. (%)**
Tier 1	1	21	Baseline	Baseline	Baseline
	2	21	7 (33.33)	8 (38.10)	6 (28.57)
	3	21	10 (47.62)	3 (14.29)	8 (38.10)
	4	21	11 (52.38)	5 (23.81)	5 (23.81)
	5	21	13 (61.90)	7 (33.33)	1 (4.76)
	6	21	12(57.14)	5 (23.81)	4 (19.05)
	7	21	8 (38.10)	3 (14.29)	10 (47.62)
Tier 2	3	23	Baseline	Baseline	Baseline
	4	20	8 (40.00)	4 (20.00)	8 (40.00)
	5	20	9 (45.00)	6 (30.00)	5 (25.00)
	6	20	8 (40.00)	4 (20.00)	8 (40.00)
	7	20	8 (40.00)	5 (25.00)	7 (35.00)

567

568 Table 3. Number (percent) of treatments per month by disease* from 10 flocks with a total of

569 approximately 2,600 sheep in England from 2014-2016

Year	Month	CODD No. (%)	SFR No. (%)	ID No. (%)	TG No. (%)	WLS No. (%)	WLA No. (%)	All No.
2014	August	0 (0)	15 (57.6)	11 (42.3)	0 (0)	0 (0)	0 (0)	26
	September	1 (3.4)	21 (72.4)	7 (24.1)	0 (0)	0 (0)	0 (0)	29
	October	0 (0)	51 (43.5)	57 (48.7)	4 (3.4)	3 (2.5)	2 (1.7)	117
	November	8 (6.6)	54 (44.6)	52 (42.9)	3 (2.4)	4 (3.3)	0 (0)	121
	December	3 (3.4)	36 (41.3)	30 (34.4)	4 (4.5)	14 (16.0)	0 (0)	87
2015	January	2 (2.0)	44 (45.8)	41 (42.7)	5 (5.2)	4 (4.1)	0 (0)	96
	February	4 (4.9)	36 (44.4)	36 (44.4)	1 (1.2)	4 (4.9)	0 (0)	81
	March	4 (4.3)	47 (51.0)	40 (43.4)	0 (0)	1 (1.0)	0 (0)	92
	April	2 (2.5)	41 (53.2)	26 (33.7)	1 (1.2)	7 (9.0)	0 (0)	77
	May	2 (3.5)	21 (36.8)	19 (33.3)	7 (12.2)	6 (10.5)	2 (3.5)	57
	June	2 (2.8)	20 (28.1)	45 (63.3)	3 (4.2)	1 (1.4)	0 (0)	71
	July	2 (2.0)	43 (43.4)	48 (48.4)	4 (4.0)	0 (0)	2 (2.0)	99
	August	1 (1.3)	26 (36.1)	36 (50.0)	8 (11.1)	1 (1.3)	0 (0)	72
	September	0 (0)	32 (47.0)	29 (42.6)	1 (1.4)	4 (5.8)	2 (2.9)	68
	October	2 (1.4)	63 (45.6)	56 (40.5)	8 (5.7)	7 (5.0)	2 (1.4)	138
	November	6 (8.1)	20 (27.0)	38 (51.3)	2 (2.7)	7 (9.4)	1 (1.3)	74
	December	0 (0)	24 (48.9)	21 (42.8)	0 (0)	0 (0)	4 (8.1)	49
2016	January	2 (2.4)	24 (29.6)	30 (37.0)	10 (12.3)	15 (18.5)	0 (0)	81
	February	1 (0.9)	21 (20.5)	60 (58.8)	8 (7.8)	10 (9.8)	2 (1.9)	102
	March	0 (0)	46 (43.8)	58 (55.2)	1 (0.9)	0 (0)	0 (0)	105

570 *CODD – contagious ovine digital dermatitis, SFR – severe footrot, ID – interdigital dermatitis, TG – toe granuloma,

571 WLS – white line separation, WLA – white line abscess

572 Table 4. Over-dispersed multi-level multivariable Poisson analysis of factors on prevalence of

573 lameness in 44 flocks in England from 2014-2016[I] with a significance level of 5% (p-value≤0.05)

Variable	Outcome	N. of Visits	% of Visits	GM % Lame	RR	95% CI
Tier	Tier 1	147	49.66	7.36	-	-
	Tier 2	149	50.34	7.58	0.99	0.81-1.20
Data Type	Baseline	90	30.41	7.94	-	-
	Intervention	206	69.59	7.26	0.99	0.84-1.17
Weeks on Plan ^1	-	-	-	-	1.07	0.99-1.15
Weeks on Plan ^2	-	-	-	-	1.00	0.99-1.00
Weeks on Plan ^3	-	-	-	-	1.00	1.00-1.00
Weeks on Plan ^4	-	-	-	-	1.00	1.00-1.00
Initial %	-	-	-	7.95	**1.04***	**1.02-1.06**
Previous Lame %	-	-	-	-	**1.03***	**1.01-1.04**
Flock housed during the last lambing season	-	253	85.47	7.83	**1.25**	**1.04-1.51**
Cull animals with 2 or more cases of lameness within a year	Uncompliant	274	92.57	7.70	-	-
	Compliant	22	7.43	4.58	**0.71***	**0.57-0.88**
Separate lame animals at all times, return to the flock when they have no signs of clinical disease	Uncompliant	169	57.09	7.53	-	-
	Compliant	127	42.91	5.20	**0.55***	**0.38-0.78**
Footbath animals during an outbreak of interdigital dermatitis	Routine use	51	17.23	8.41	-	-
	No footbath	78	26.35	7.65	1.07	0.92-1.24
	Compliant	167	56.42	7.10	**0.87**	**0.77-0.99**
If annual or point lameness prevalence ≥10%, vaccinate every 4-6 months or before risk period	Uncompliant	210	70.95	7.62	-	-
	Compliant	68	22.97	7.43	0.88	0.78-1.00
	Vaccine not recommended	18	6.08	5.87	**0.65***	**0.49-0.85**

574 Variance (s.e.) between flocks = 0.013 (0.007) and between visits = 3.067(0.272)

575 No. = number, % = percentage, GM = geometric mean, Bold = Wald test p≤0.05, * = Wald test p≤0.01

Figure 1. Boxplots of the prevalence of lameness in 44 sheep flocks in England in 2014-2016 by visit and tier

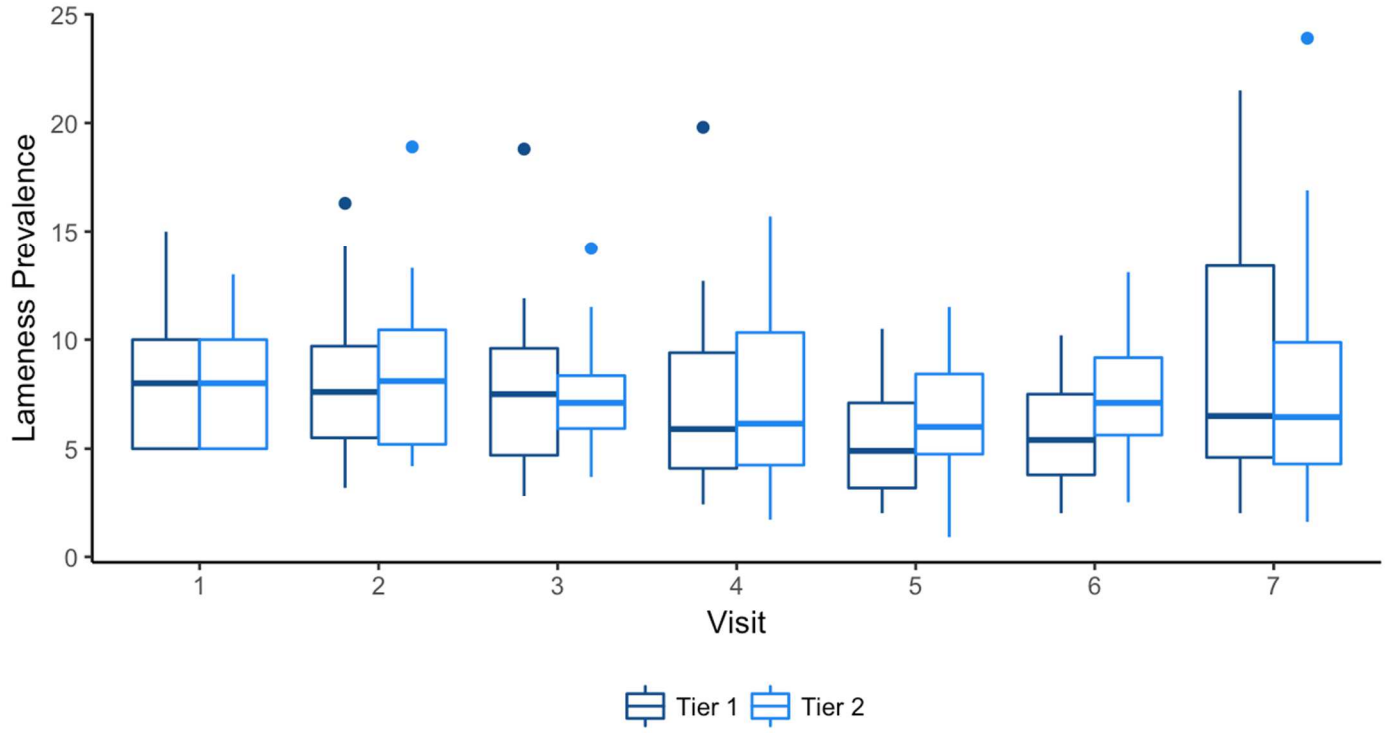


Figure 2. Boxplots of prevalence of lameness in 44 sheep flocks in England in 2014-2016 by visit and tier in each region*

Figure 2a. East region, 10 flocks

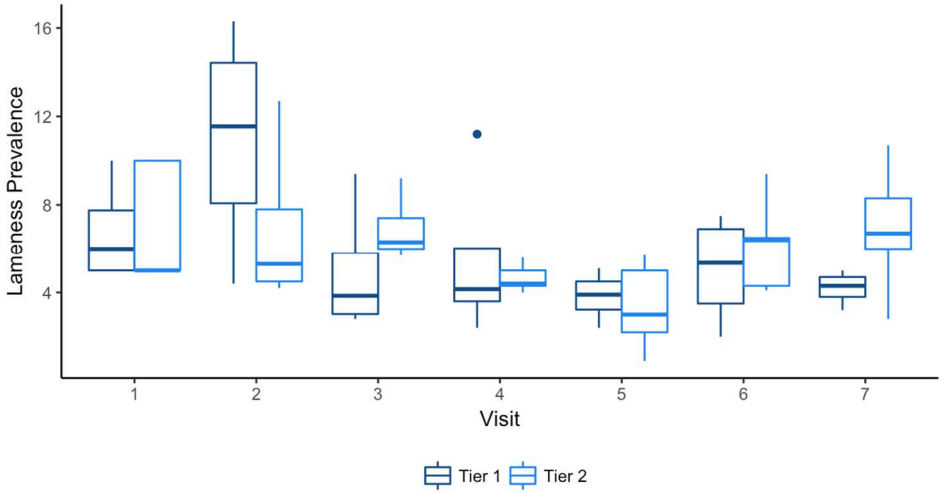


Figure 2c. North region, 10 flocks

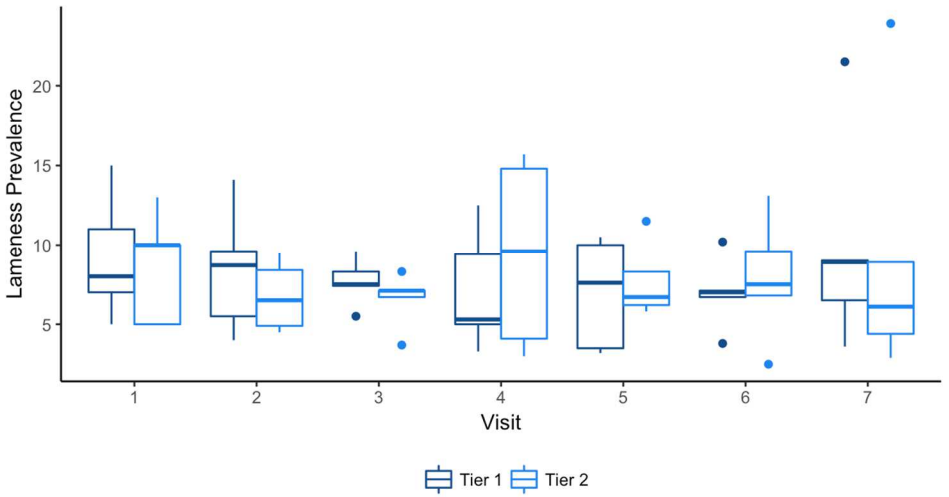


Figure 2b. West region, 12 flocks

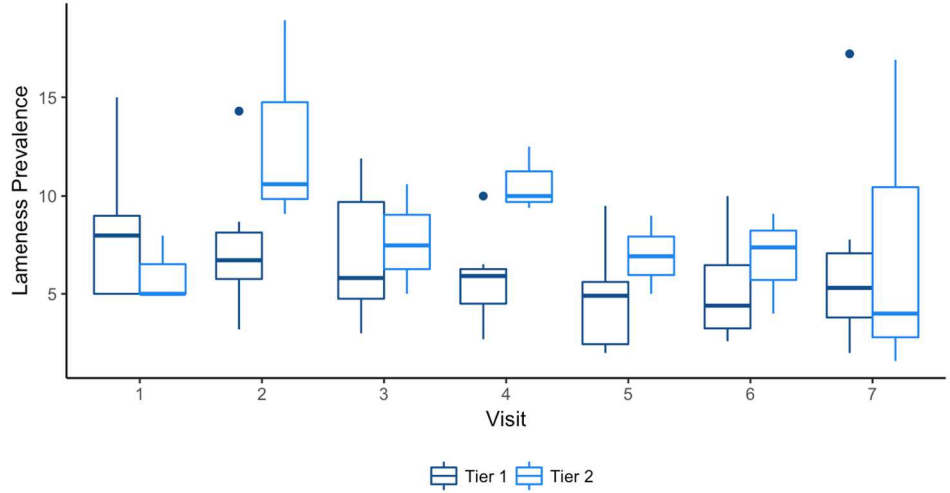
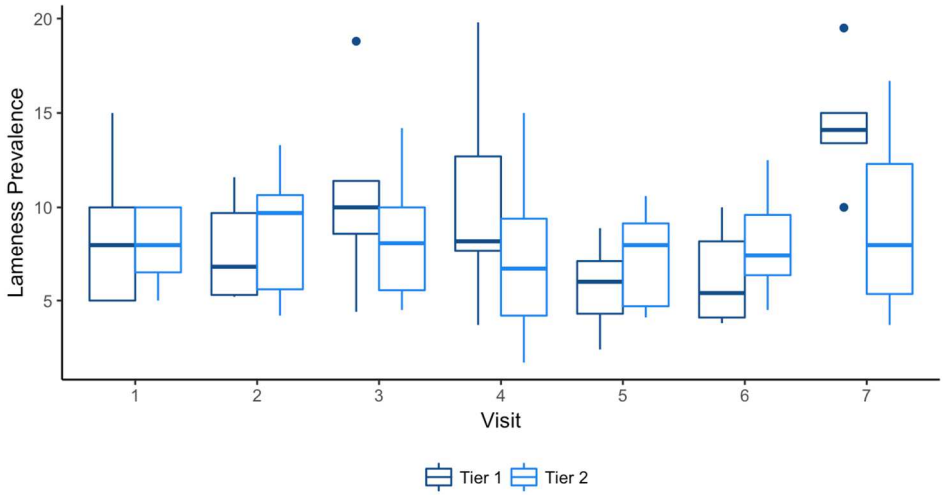


Figure 2d. South region, 12 flocks



*East - Norfolk, Lincolnshire, Hertfordshire, Bedfordshire, and South Yorkshire; West – West Midlands, Herefordshire, Gloucestershire, Oxfordshire, Staffordshire, Cheshire, and Shropshire; North – West Yorkshire, North Yorkshire, Cumbria, Northumberland, and Durham; South – Somerset, Devon, and Cornwall

Figure 3. Geometric mean lameness prevalence and standard errors for 41 flocks in England in 2014-2016 by significant decrease or increase in prevalence of lameness compared with the baseline visit (a) tier 1 = visit 1, (b) tier 2 = visit 3 using the reliable change index

Figure 3a. Tier 1 flocks with significant increased or decreased lameness prevalence

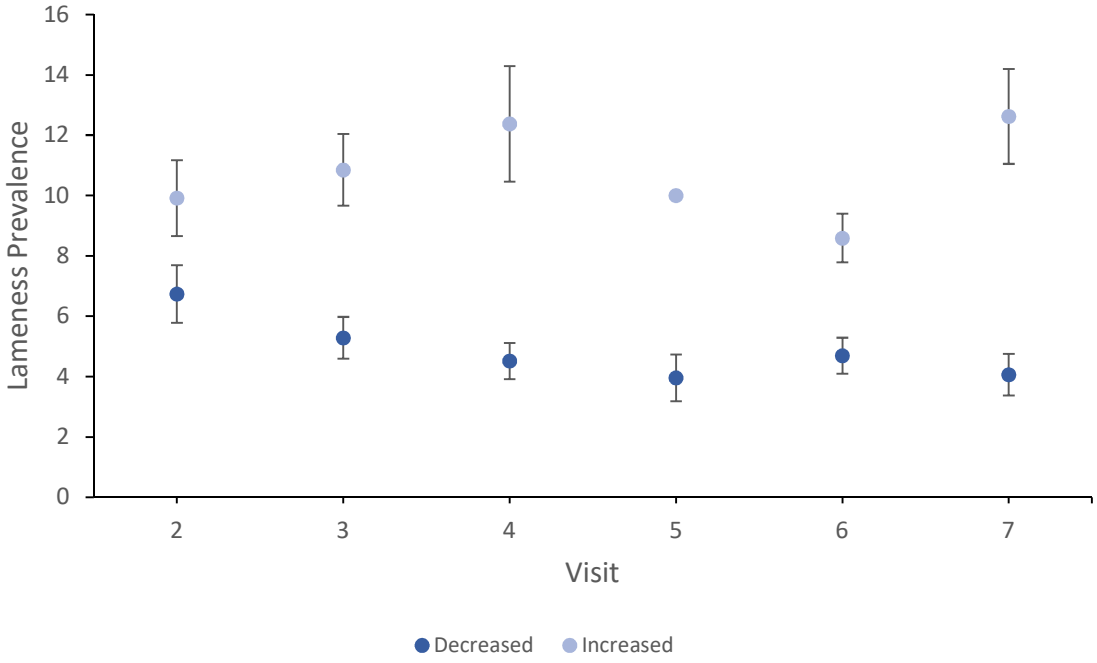


Figure 3b. Tier 2 flocks with significantly increased or decreased lameness prevalence

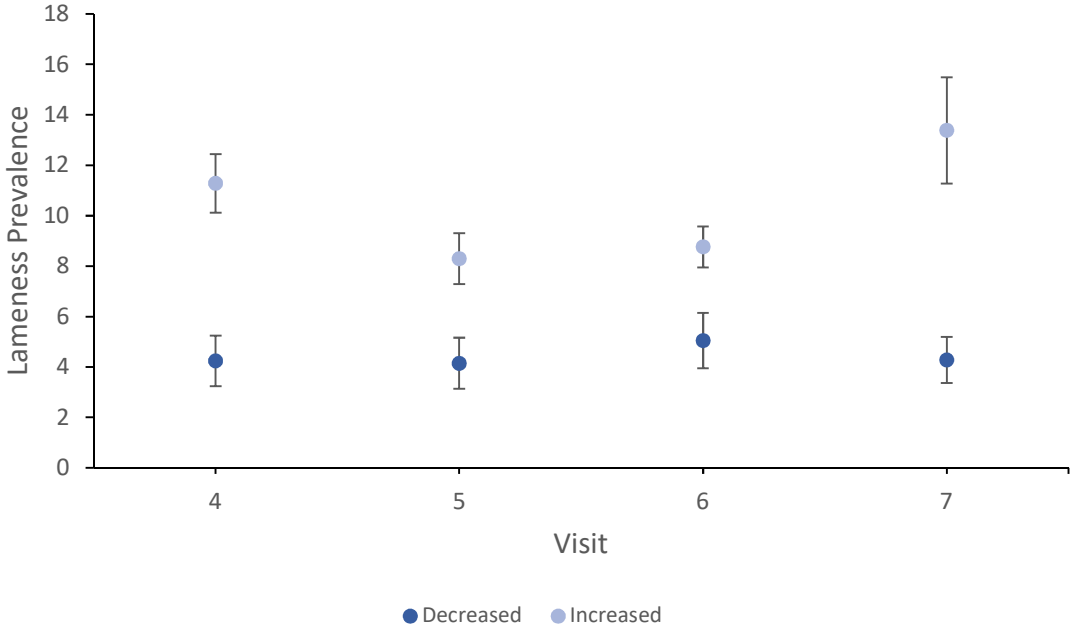
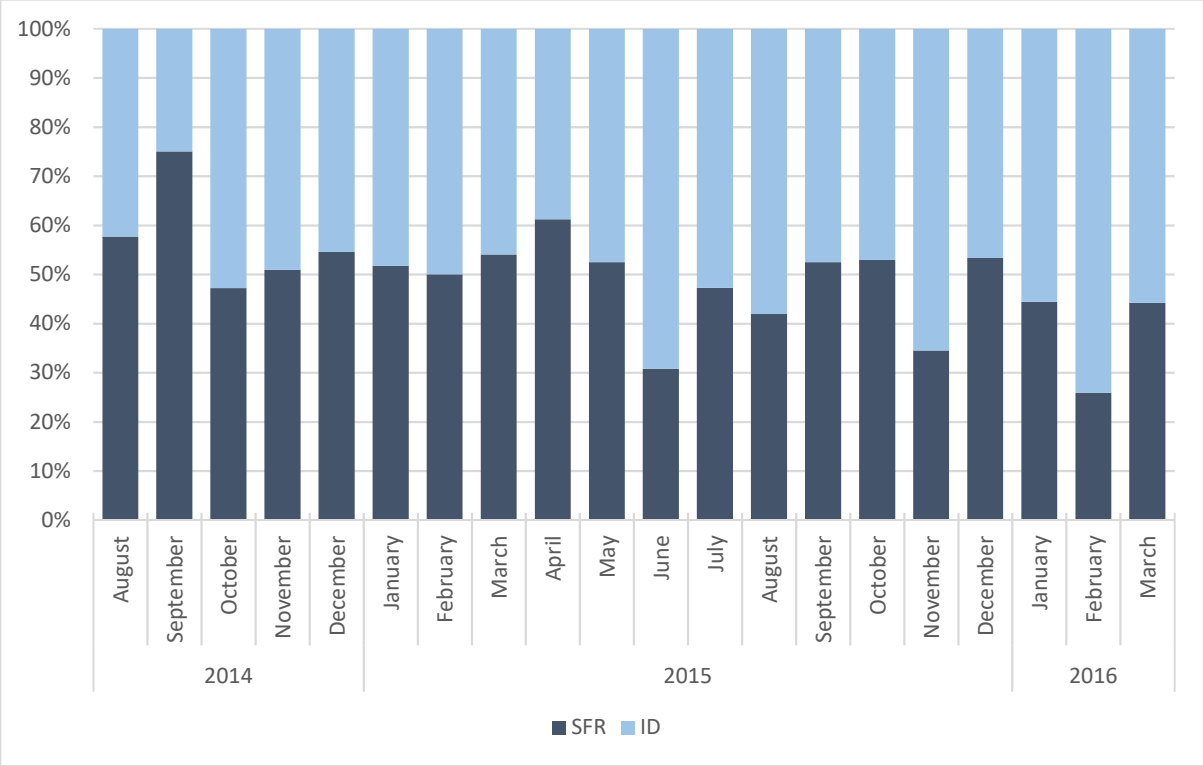
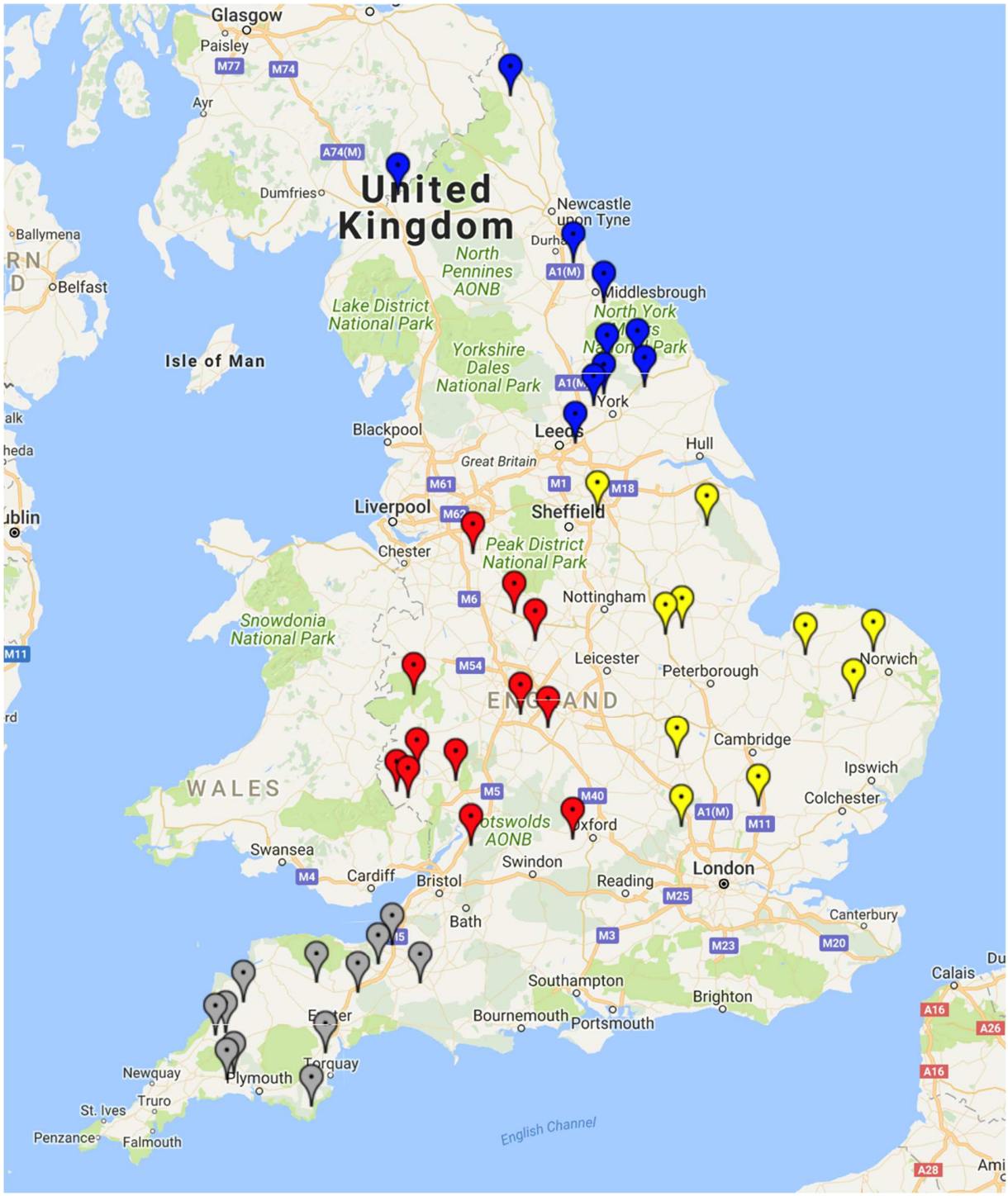


Figure 4. Percentage of reported lameness treatments for cases of *Dichelobacter nodosus* infection that presented as either interdigital dermatitis (ID) or severe footrot (SFR) in 10 flocks in England from 2014-2016

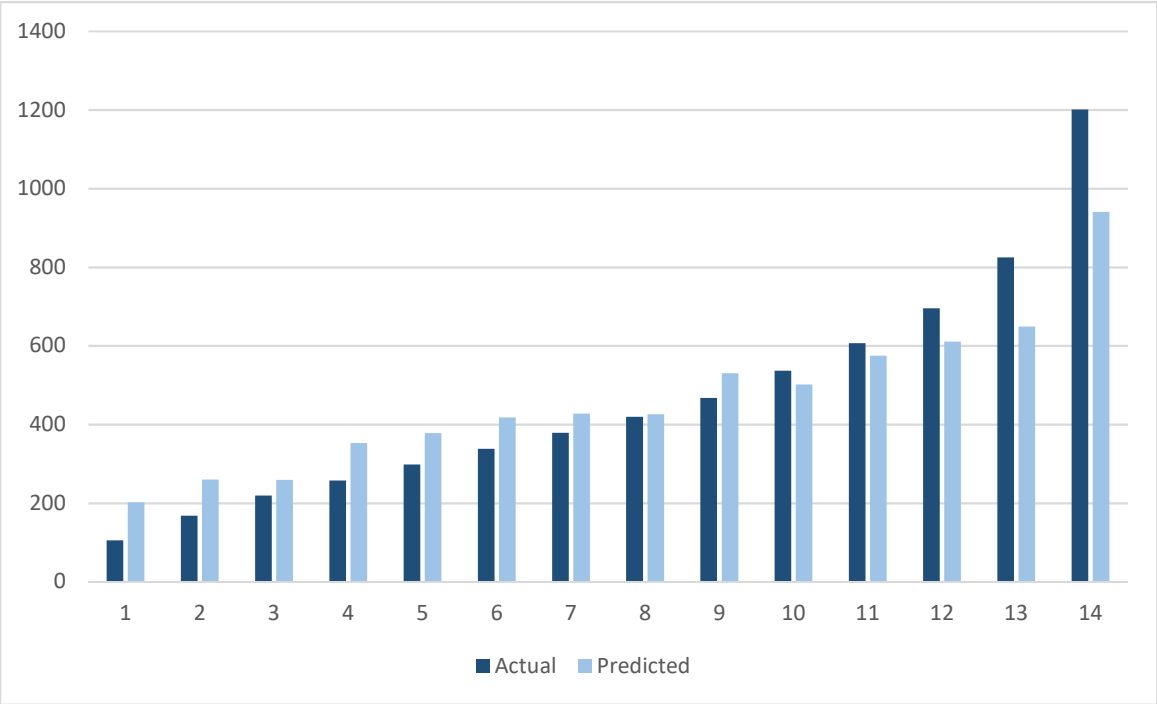


Supplementary Figure 1: Map displaying location of 44 study flocks in England, colour coded by region*



*North - blue, West – red, East – yellow, South – grey; Image created using an open source online tool (https://www.doogal.co.uk/BatchGeocoding.php)

Supplementary Figure 2. Comparison of recorded numbers of lame sheep per farm per visit (Actual), grouped into 14 ascending quantiles, and their associated predicted values (Predicted) from a multivariable over-dispersed Poisson model fitted to data from 44 English sheep flocks from 2014-2016



Supplementary Table 1. The number (percent) of 44 sheep flocks in England in 2014-2016 by compliance with management practices in the lameness control plan by visit

Management activity	Compliance	Visit 1 No. (%)	Visit 2 No. (%)	Visit 3 No. (%)	Visit 4 No. (%)	Visit 5 No. (%)	Visit 6 No. (%)	Visit 7 No. (%)
No routine foot trimming	**Compliant**	**24 (54.5)**	**30 (68.2)**	**30 (68.2)**	**36 (87.8)**	**36 (87.8)**	**39 (95.1)**	**39 (95.1)**
	Uncompliant	**20 (45.5)**	**14 (31.8)**	**14 (31.8)**	**5 (12.2)**	**5 (12.2)**	**2 (4.9)**	**2 (4.9)**
Daily inspection of flock	Missing*	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	38 (86.4)	38 (86.4)	38 (86.4)	36 (87.8)	36 (87.8)	37 (90.2)	37 (90.2)
	Uncompliant	5 (11.4)	5 (11.4)	5 (11.4)	5 (12.2)	5 (12.2)	4 (9.8)	4 (9.8)
Treat lame sheep within 3 days	Compliant	12 (27.3)	11 (25)	11 (25)	10 (24.4)	10 (24.4)	8 (19.5)	8 (19.5)
	Uncompliant	32 (72.7)	33 (75)	33 (75)	31 (75.6)	31 (75.6)	33 (80.5)	33 (80.5)
Treat severe footrot with long-acting antibiotic injection and topical spray	**Compliant**	**7 (15.9)**	**16 (36.4)**	**16 (36.4)**	**23 (56.1)**	**23 (56.1)**	**31 (75.6)**	**31 (75.6)**
	Not Advised**	**0 (0)**	**0 (0)**	**0 (0)**	**10 (24.4)**	**10 (24.4)**	**2 (4.9)**	**2 (4.9)**
	Uncompliant	**37 (84.1)**	**28 (63.6)**	**28 (63.6)**	**8 (19.5)**	**8 (19.5)**	**8 (19.5)**	**8 (19.5)**
Treat contagious ovine digital dermatitis with long-acting antibiotic injection and topical spray	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	19 (43.2)	13 (29.5)	13 (29.5)	9 (22)	9 (22)	13 (31.7)	13 (31.7)
	Not Advised	20 (45.5)	28 (63.6)	28 (63.6)	28 (68.3)	28 (68.3)	27 (65.9)	27 (65.9)
	Uncompliant	4 (9.1)	2 (4.5)	2 (4.5)	4 (9.8)	4 (9.8)	1 (2.4)	1 (2.4)
Treat ewes with interdigital dermatitis with long-acting antibiotic injection and topical spray	**Missing**	**3 (6.8)**	**3 (6.8)**	**3 (6.8)**	**0 (0)**	**0 (0)**	**0 (0)**	**0 (0)**
	Compliant	**2 (4.5)**	**6 (13.6)**	**6 (13.6)**	**5 (12.2)**	**5 (12.2)**	**6 (14.6)**	**6 (14.6)**
	Uncompliant	**39 (88.6)**	**35 (79.5)**	**35 (79.5)**	**36 (87.8)**	**36 (87.8)**	**35 (85.4)**	**35 (85.4)**
Treat lambs with interdigital dermatitis with topical spray only	**Compliant**	**23 (52.3)**	**29 (65.9)**	**29 (65.9)**	**32 (78)**	**32 (78)**	**30 (73.2)**	**30 (73.2)**
	Uncompliant	**21 (47.7)**	**15 (34.1)**	**15 (34.1)**	**9 (22)**	**9 (22)**	**11 (26.8)**	**11 (26.8)**
Remove debris in white line separations and treat with long-acting antibiotic injection and topical spray if infected	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	9 (20.5)	9 (20.5)	9 (20.5)	6 (14.6)	6 (14.6)	9 (22)	9 (22)
	Not Advised	20 (45.5)	24 (54.5)	24 (54.5)	27 (65.9)	27 (65.9)	25 (61)	25 (61)
	Uncompliant	14 (31.8)	10 (22.7)	10 (22.7)	8 (19.5)	8 (19.5)	7 (17.1)	7 (17.1)
Treat white line abscesses with long-acting antibiotic injection and spray, trim carefully to open if not draining	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	15 (34.1)	10 (22.7)	10 (22.7)	9 (22)	9 (22)	8 (19.5)	8 (19.5)
	Not Advised	20 (45.5)	28 (63.6)	28 (63.6)	30 (73.2)	30 (73.2)	30 (73.2)	30 (73.2)
	Uncompliant	8 (18.2)	5 (11.4)	5 (11.4)	2 (4.9)	2 (4.9)	3 (7.3)	3 (7.3)
Do not trim diseased feet as a part of treatment	**Compliant**	**2 (4.5)**	**12 (27.3)**	**12 (27.3)**	**23 (56.1)**	**23 (56.1)**	**21 (51.2)**	**21 (51.2)**
	Uncompliant	**42 (95.5)**	**32 (72.7)**	**32 (72.7)**	**18 (43.9)**	**18 (43.9)**	**20 (48.8)**	**20 (48.8)**
Keep treating lame sheep throughout pregnancy	Compliant	0 (0)	0 (0)	0 (0)	19 (46.3)	19 (46.3)	22 (53.7)	22 (53.7)
	Not Advised	44 (100)	44 (100)	44 (100)	1 (2.4)	1 (2.4)	1 (2.4)	1 (2.4)

	Uncompliant	0 (0)	0 (0)	0 (0)	21 (51.2)	21 (51.2)	18 (43.9)	18 (43.9)
Treat toe granulomas with anti-inflammatory medication, consider culling the sheep	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	2 (4.5)	2 (4.5)	2 (4.5)	1 (2.4)	1 (2.4)	1 (2.4)	1 (2.4)
	Not Advised	13 (29.5)	16 (36.4)	16 (36.4)	21 (51.2)	21 (51.2)	26 (63.4)	26 (63.4)
	Uncompliant	28 (63.6)	25 (56.8)	25 (56.8)	19 (46.3)	19 (46.3)	14 (34.1)	14 (34.1)
Footbath during outbreaks of interdigital dermatitis	Compliant	35 (79.5)	27 (61.4)	27 (61.4)	23 (56.1)	23 (56.1)	16 (39)	16 (39)
	Not Advised	4 (9.1)	12 (27.3)	12 (27.3)	12 (29.3)	12 (29.3)	13 (31.7)	13 (31.7)
	Uncompliant	5 (11.4)	5 (11.4)	5 (11.4)	6 (14.6)	6 (14.6)	12 (29.3)	12 (29.3)
Treat lame sheep within 1 week	Compliant	36 (81.8)	33 (75)	33 (75)	24 (58.5)	24 (58.5)	27 (65.9)	27 (65.9)
	Uncompliant	8 (18.2)	11 (25)	11 (25)	17 (41.5)	17 (41.5)	14 (34.1)	14 (34.1)
Vaccinate every 4-6 months or 2-4 weeks before known risk periods	**Compliant**	**8 (18.2)**	**10 (22.7)**	**10 (22.7)**	**10 (24.4)**	**10 (24.4)**	**10 (24.4)**	**10 (24.4)**
	Not Advised	**0 (0)**	**1 (2.3)**	**1 (2.3)**	**4 (9.8)**	**4 (9.8)**	**4 (9.8)**	**4 (9.8)**
	Uncompliant	**36 (81.8)**	**33 (75)**	**33 (75)**	**27 (65.9)**	**27 (65.9)**	**27 (65.9)**	**27 (65.9)**
Isolate new and returning sheep for 28+ days	Compliant	11 (25)	16 (36.4)	16 (36.4)	10 (24.4)	10 (24.4)	4 (9.8)	4 (9.8)
	Not Advised	1 (2.3)	7 (15.9)	7 (15.9)	16 (39)	16 (39)	27 (65.9)	27 (65.9)
	Uncompliant	32 (72.7)	21 (47.7)	21 (47.7)	15 (36.6)	15 (36.6)	10 (24.4)	10 (24.4)
Inspect all feet of new and returning sheep, treat as needed	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	11 (25)	10 (22.7)	10 (22.7)	6 (14.6)	6 (14.6)	5 (12.2)	5 (12.2)
	Not Advised	1 (2.3)	7 (15.9)	7 (15.9)	16 (39)	16 (39)	27 (65.9)	27 (65.9)
	Uncompliant	31 (70.5)	26 (59.1)	26 (59.1)	19 (46.3)	19 (46.3)	9 (22)	9 (22)
Separate lame sheep at all times, return to the flock when they have no signs of clinical disease	**Compliant**	**0 (0)**	**2 (4.5)**	**2 (4.5)**	**1 (2.4)**	**1 (2.4)**	**1 (2.4)**	**1 (2.4)**
	Uncompliant	**44 (100)**	**42 (95.5)**	**42 (95.5)**	**40 (97.6)**	**40 (97.6)**	**40 (97.6)**	**40 (97.6)**
Separate lame sheep at key times of year, return to the flock when they have no signs of clinical disease	**Compliant**	**0 (0)**	**2 (4.5)**	**2 (4.5)**	**6 (14.6)**	**6 (14.6)**	**2 (4.9)**	**2 (4.9)**
	Uncompliant	**44 (100)**	**42 (95.5)**	**42 (95.5)**	**35 (85.4)**	**35 (85.4)**	**39 (95.1)**	**39 (95.1)**
No co-grazing with cattle	**Missing**	**1 (2.3)**	**1 (2.3)**	**1 (2.3)**	**0 (0)**	**0 (0)**	**0 (0)**	**0 (0)**
	Compliant	**9 (20.5)**	**9 (20.5)**	**9 (20.5)**	**9 (22)**	**9 (22)**	**10 (24.4)**	**10 (24.4)**
	Not Advised	**15 (34.1)**	**15 (34.1)**	**15 (34.1)**	**15 (36.6)**	**15 (36.6)**	**15 (36.6)**	**15 (36.6)**
	Uncompliant	**19 (43.2)**	**19 (43.2)**	**19 (43.2)**	**17 (41.5)**	**17 (41.5)**	**16 (39)**	**16 (39)**
Spread lime in high moisture areas	**Missing**	**3 (6.8)**	**3 (6.8)**	**3 (6.8)**	**0 (0)**	**0 (0)**	**0 (0)**	**0 (0)**
	Compliant	**7 (15.9)**	**8 (18.2)**	**8 (18.2)**	**7 (17.1)**	**7 (17.1)**	**12 (29.3)**	**12 (29.3)**
	Uncompliant	**34 (77.3)**	**33 (75)**	**33 (75)**	**34 (82.9)**	**34 (82.9)**	**29 (70.7)**	**29 (70.7)**
Footbath all sheep when in for other treatment only; do not gather for routine footbathing	Compliant	22 (50)	27 (61.4)	27 (61.4)	21 (51.2)	21 (51.2)	22 (53.7)	22 (53.7)
	Not Advised	4 (9.1)	7 (15.9)	7 (15.9)	7 (17.1)	7 (17.1)	8 (19.5)	8 (19.5)
	Uncompliant	18 (40.9)	10 (22.7)	10 (22.7)	13 (31.7)	13 (31.7)	11 (26.8)	11 (26.8)
Cull sheep with 2 or more cases of lameness within a year	**Compliant**	**0 (0)**	**1 (2.3)**	**1 (2.3)**	**4 (9.8)**	**4 (9.8)**	**6 (14.6)**	**6 (14.6)**
	Uncompliant	**44 (100)**	**43 (97.7)**	**43 (97.7)**	**37 (90.2)**	**37 (90.2)**	**35 (85.4)**	**35 (85.4)**

Avoid selecting replacements from offspring of ewes being culled for lameness reasons	Compliant	11 (25)	8 (18.2)	8 (18.2)	5 (12.2)	5 (12.2)	5 (12.2)	5 (12.2)
	Not Advised	14 (31.8)	20 (45.5)	20 (45.5)	16 (39)	16 (39)	26 (63.4)	26 (63.4)
	Uncompliant	19 (43.2)	16 (36.4)	16 (36.4)	20 (48.8)	20 (48.8)	10 (24.4)	10 (24.4)
Inspect all sheep before purchasing them	Compliant	21 (47.7)	27 (61.4)	27 (61.4)	16 (39)	16 (39)	10 (24.4)	10 (24.4)
	Not Advised	3 (6.8)	8 (18.2)	8 (18.2)	17 (41.5)	17 (41.5)	27 (65.9)	27 (65.9)
	Uncompliant	20 (45.5)	9 (20.5)	9 (20.5)	8 (19.5)	8 (19.5)	4 (9.8)	4 (9.8)
Purchase all sheep from a single private source	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	14 (31.8)	14 (31.8)	14 (31.8)	11 (26.8)	11 (26.8)	7 (17.1)	7 (17.1)
	Not Advised	2 (4.5)	7 (15.9)	7 (15.9)	16 (39)	16 (39)	27 (65.9)	27 (65.9)
	Uncompliant	27 (61.4)	22 (50)	22 (50)	14 (34.1)	14 (34.1)	7 (17.1)	7 (17.1)
Cull sheep with 3 or more cases of lameness within a year	**Compliant**	**16 (36.4)**	**17 (38.6)**	**17 (38.6)**	**20 (48.8)**	**20 (48.8)**	**18 (43.9)**	**18 (43.9)**
	Uncompliant	**28 (63.6)**	**27 (61.4)**	**27 (61.4)**	**21 (51.2)**	**21 (51.2)**	**23 (56.1)**	**23 (56.1)**
Ask sellers for flock disease and lameness history	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	14 (31.8)	13 (29.5)	13 (29.5)	8 (19.5)	8 (19.5)	8 (19.5)	8 (19.5)
	Not Advised	2 (4.5)	8 (18.2)	8 (18.2)	17 (41.5)	17 (41.5)	27 (65.9)	27 (65.9)
	Uncompliant	27 (61.4)	22 (50)	22 (50)	16 (39)	16 (39)	6 (14.6)	6 (14.6)
Rest pastures for 2+ weeks between grazing groups	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	23 (52.3)	22 (50)	22 (50)	21 (51.2)	21 (51.2)	22 (53.7)	22 (53.7)
	Not Advised	10 (22.7)	11 (25)	11 (25)	11 (26.8)	11 (26.8)	11 (26.8)	11 (26.8)
	Uncompliant	10 (22.7)	10 (22.7)	10 (22.7)	9 (22)	9 (22)	8 (19.5)	8 (19.5)
Have a separate field/pen for sheep isolation	**Compliant**	**0 (0)**	**1 (2.3)**	**1 (2.3)**	**2 (4.9)**	**2 (4.9)**	**2 (4.9)**	**2 (4.9)**
	Uncompliant	**44 (100)**	**43 (97.7)**	**43 (97.7)**	**39 (95.1)**	**39 (95.1)**	**39 (95.1)**	**39 (95.1)**
Top up bedding frequently during housing to keep the environment dry under-foot	Compliant	19 (43.2)	20 (45.5)	20 (45.5)	18 (43.9)	18 (43.9)	19 (46.3)	19 (46.3)
	Not Advised	6 (13.6)	6 (13.6)	6 (13.6)	6 (14.6)	6 (14.6)	4 (9.8)	4 (9.8)
	Uncompliant	19 (43.2)	18 (40.9)	18 (40.9)	17 (41.5)	17 (41.5)	18 (43.9)	18 (43.9)
Disinfect individual pens after each use during housing	**Missing**	**3 (6.8)**	**3 (6.8)**	**3 (6.8)**	**0 (0)**	**0 (0)**	**0 (0)**	**0 (0)**
	Compliant	**7 (15.9)**	**7 (15.9)**	**7 (15.9)**	**8 (19.5)**	**8 (19.5)**	**14 (34.1)**	**14 (34.1)**
	Not Advised	**6 (13.6)**	**6 (13.6)**	**6 (13.6)**	**6 (14.6)**	**6 (14.6)**	**4 (9.8)**	**4 (9.8)**
	Uncompliant	**28 (63.6)**	**28 (63.6)**	**28 (63.6)**	**27 (65.9)**	**27 (65.9)**	**23 (56.1)**	**23 (56.1)**
Stock-proof fencing for all property boundaries and isolation areas	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	37 (84.1)	37 (84.1)	37 (84.1)	35 (85.4)	35 (85.4)	35 (85.4)	35 (85.4)
	Uncompliant	6 (13.6)	6 (13.6)	6 (13.6)	6 (14.6)	6 (14.6)	6 (14.6)	6 (14.6)
Scrape out group pens and re-bed them at least once during housing	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	10 (22.7)	11 (25)	11 (25)	11 (26.8)	11 (26.8)	8 (19.5)	8 (19.5)
	Not Advised	7 (15.9)	7 (15.9)	7 (15.9)	6 (14.6)	6 (14.6)	4 (9.8)	4 (9.8)
	Uncompliant	26 (59.1)	25 (56.8)	25 (56.8)	24 (58.5)	24 (58.5)	29 (70.7)	29 (70.7)
Double-fence all property boundaries shared with neighbours with livestock	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	11 (25)	11 (25)	11 (25)	10 (24.4)	10 (24.4)	11 (26.8)	11 (26.8)

	Not Advised	10 (22.7)	10 (22.7)	10 (22.7)	10 (24.4)	10 (24.4)	10 (24.4)	10 (24.4)
	Uncompliant	22 (50)	22 (50)	22 (50)	21 (51.2)	21 (51.2)	20 (48.8)	20 (48.8)
Stock-proof fencing for all fences	Missing	1 (2.3)	1 (2.3)	1 (2.3)	0 (0)	0 (0)	0 (0)	0 (0)
	Compliant	31 (70.5)	31 (70.5)	31 (70.5)	30 (73.2)	30 (73.2)	30 (73.2)	30 (73.2)
	Uncompliant	12 (27.3)	12 (27.3)	12 (27.3)	11 (26.8)	11 (26.8)	11 (26.8)	11 (26.8)

Bold – Recommendations that saw an increase in compliance during the study; *Missing – flocks where compliance could not be ascertained; **Not Advised - flocks where the activity was not recommended

Supplementary Table 2. Number (percent) of sheep in a flock that were lame on ≥2 or ≥3 occasions in a calendar year in 10 flocks in England from 2014-2016

Flock ID	Flock size	Lame ≥2/year No. (%)	Lame ≥3/year No. (%)
DM0940	200	13 (6.5)	4 (2.0)
DM2346	300	6 (2.0)	1 (0.3)
DM3165	130	10 (7.7)	4 (3.1)
DM3583	400	11 (2.8)	3 (0.8)
DM1946	200	12 (6.0)	0 (0.0)
DM2533	300	20 (6.7)	7 (2.3)
DM3474	400	8 (2.0)	2 (0.5)
DM3875	260	31 (11.9)	14 (5.4)
DM2517	320	7 (2.2)	2 (0.6)
DM5301	113	16 (14.2)	5 (4.4)

Supplementary Table 3. Univariable over-dispersed Poisson random effects analysis of 46 factors associated with prevalence of lameness of 44 flocks in England in 2014-2016 with a significance level of 5% (p-value≤0.05)

Variable	RR	95% CI
No routine foot trimming	0.96	0.84-1.11
Daily inspection of flock	0.99	0.75-1.30
Treat lame sheep within 3 days	0.92	0.80-1.06
Treat severe footrot with long-acting antibiotics and topical spray	1.06	0.94-1.19
Treat contagious ovine digital dermatitis with long-acting antibiotics and topical spray	**1.46**	**1.11-1.93**
Treat ewes with interdigital dermatitis with long-acting antibiotics and topical spray	0.94	0.76-1.17
Treat lambs with interdigital dermatitis with topical spray only	1.07	0.94-1.23
Remove debris in shelly hoof and treat with long-acting antibiotics and topical spray if infected	1.12	0.94-1.33
Treat white line abscesses with long-acting antibiotics and topical spray	0.82	0.66-1.02
Do not trim diseased feet as a form of treatment	0.92	0.82-1.04
Keep treating lame sheep throughout pregnancy	1.00	0.82-1.04
Treat toe granulomas with anti-inflammatory, consider culling the sheep	1.01	0.68-1.50
Footbath during outbreaks of interdigital dermatitis	0.91	0.78-1.06
Treat lame sheep within 1 week	1.02	0.90-1.15
Vaccinate every 4-6 months or 2-4 weeks before risk period	0.96	0.81-1.14
Isolate new and returning sheep for 28+ days	1.04	0.90-1.20
Inspect all feet of new and returning sheep, treat as needed	0.94	0.80-1.11
Separate lame sheep at all times, return to the flock when they have no signs of clinical disease	**0.51**	**0.34-0.78**
Separate lame sheep at key times of year, return to the flock when they have no signs of clinical disease	0.98	0.79-1.22
No co-grazing with cattle	0.91	0.81-1.06
Spread lime in high moisture areas	0.98	0.82-1.17
Footbath all sheep when in for other treatment; do not gather for routine footbathing	0.93	0.81-1.06
Cull sheep with 2 or more cases of lameness within a year	**0.66**	**0.52-0.84**
Avoid selecting replacements from offspring of ewes being culled for lameness reasons	0.87	0.73-1.05
Inspect all sheep before purchasing them	**1.17**	**1.01-1.36**
Purchase all sheep from a single private source	1.01	0.87-1.17
Cull sheep with 3 or more cases of lameness within a year	0.94	0.82-1.07
Ask sellers for flock disease and lameness history	0.92	0.78-1.08
Rest pastures for 2+ weeks between grazing groups	0.96	0.81-1.15
Have a separate field/pen for sheep isolation	**0.63**	**0.45-0.88**
Top up bedding frequently during housing to keep the environment dry under-foot	1.01	0.89-1.15
Disinfect individual pens after each use during housing	1.13	0.96-1.32
Stock-proof fencing for all property boundaries and isolation areas	1.15	0.88-1.49

Scrape out group pens and re-bed them at least once during housing	1.01	0.86-1.18
Double-fence all property boundaries shared with neighbours with livestock	1.23	0.99-1.52
Stock-proof fencing for all fences	1.08	0.88-1.32
Flock housed in previous 6 months – Yes	1.07	0.95-1.19
Flock housed in previous lambing season - Yes	**1.43**	**1.15-1.77**
Weeks in housing	1.01	1.00-1.02
Lameness prevalence at previous visit (0.93-19.00)	**1.05**	**1.03-1.07**
Initial lameness prevalence (5.00-15.00)	**1.05**	**1.03-1.08**
Weeks on lameness control plan ^1	1.02	0.99-1.04
Weeks on lameness control plan ^2	1.00	1.00-1.00
Weeks on lameness control plan ^3	1.00	1.00-1.00
Weeks on lameness control plan ^4	1.00	1.00-1.00
Weeks on study ^1	1.00	0.98-1.03
Weeks on study ^2	1.00	1.00-1.00
Weeks on study ^3	1.00	1.00-1.00
Weeks on study ^4	1.00	1.00-1.00
Avg. temp (°C) from the prev. month (3.5-18.6)	1.00	0.99-1.02
Total rainfall (mm) in the prev. month (13.1-261.8)	1.00	1.00-1.00
CODD ever reported in flock - Yes	1.17	0.97-1.40
Kept accurate records – Yes	0.98	0.88-1.10
Tier – Tier 2	1.05	0.87-1.26
Data type – Treatment	1.00	0.90-1.11

Supplementary Table 4. Analysis of 4 factors forced into a multi-variable over-dispersed Poisson random effects model associated with underlying patterns in the prevalence of lameness of 44 flocks in England in 2014-2016 with a significance level of 5% (p-value≤0.05)

Variable	Coefficient	SE	RR	95% CI
Weeks on lameness control plan ^1	9.09E-02	3.99E-02	**1.10**	**1.01-1.18**
Weeks on lameness control plan ^2	-4.38E-03	1.80E-03	**1.00**	**0.99-1.00**
Weeks on lameness control plan ^3	7.84E-05	3.14E-05	**1.00**	**1.00-1.00**
Weeks on lameness control plan ^4	-4.60E-07	1.90E-07	**1.00**	**1.00-1.00**
Tier 1 vs Tier 2 - Tier 1	1.25E-01	6.85E-02	1.13	0.99-1.30
Treatment data vs Control data - Control	-5.06E-01	2.72E-01	0.60	0.35-1.03
Lameness prevalence at previous visit	3.95E-02	8.32E-03	**1.04**	**1.02-1.06**
Initial lameness prevalence	3.27E-02	1.04E-02	**1.03**	**1.01-1.05**